MICROWAVE BEHAVIOR OF FERRITES: THEORY AND EXPERIMENT

Richard G. Geyer
National Institute of Standards and Technology, 325 Broadway, Boulder, CO 80303 U.S.A.
Jerzy Krupka
Instytut Mikroelektroniki i Optoelektroniki Politechniki Warszawskiej, Koszykowa 75, 00-662 Warszawa, POLAND

1 Abstract

The relative magnetic permeability and loss factor of microwave ferrites in the demagnetized state are determined near and above gyromagnetic resonance using low-loss dielectric ring resonators. This technique allows complex permeability determination on a *single* ferrite sample from 2 GHz to 25 GHz. The measured real parts of the initial permeability are compared with theoretical predictions of the permeability of a sample in the demagnetized state.

2 Introduction

For optimal design of microwave circulators and phase shifters, low power insertion phase and loss properties of ferrites at the operational frequency are needed. These properties cannot generally be predicted on the basis of saturation magnetization and ferromagnetic linewidth and are not usually specified by manufacturers. This paper addresses accurate measurements of the scalar complex permeability of microwave ferrites in the low-loss frequency region (near and above natural gyromagnetic resonance). At these frequencies magnetic losses are on the order of 10^{-2} to 10^{-5} and cannot be accurately measured by transmission line methods. Here cylindrical H_{011} low-loss dielectric ring resonators, having complex permittivity $\epsilon_r^* = \epsilon_r' - j\epsilon_r''$, are used. The permeability and magnetic loss factor of the ferrite under test are computed from measured H_{011} resonant frequencies and Q factors of these resonators with and without the ferrite sample.

3 Measurements

The resonant sytem which was used to measure the microwave complex permeability of ferrite samples is shown in Fig. 1. In the absence of an applied static field, the ferrite in the demagnetized state is isotropic and reciprocal and is described by a scalar frequency-dependent permeability, $\mu_d^* = \mu_d' - j\mu_d''$, and complex permittivity, $\epsilon_f^* = \epsilon_f' - j\epsilon_f''$. The aspect ratios and permittivities of the dielectric resonators were chosen so as to enable spectral characterization of a single ferrite sample over a broad range in frequency. The resonators are coupled to the external microwave source through

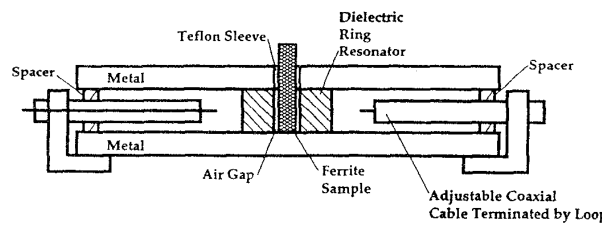

Figure 1: Parallel-plate H_{011} resonant system used in permeability measurements.

two loop-terminated coaxial cables that are adjustable so that the measured loaded Q factor is equal to the unloaded Q factor within any prescribed accuracy. The air gap, which always exists between the ferrite sample and the dielectric ring resonator, is rigorously taken into account in the eigenvalue equation solution [1,2].

As a first step, the complex permittivity of the ferrite sample, as specified by the manufacturer, is verified with a TM_{0n0} cavity. Second, the complex permittivities of each dielectric ring resonator are found from measurements of the resonant frequencies and unloaded Q factors of the empty ring resonators operating in the H_{011} mode, given the dimensions of the resonators and taking into account conductive microwave losses of the upper and lower ground planes. Values of the imaginary parts of ϵ_f^* and ϵ_r^* at other measurement frequencies are then calculated assuming a linear increase with frequency. Next, the scalar permeability μ_d' is determined from measurements of the resonant frequency of the ring resonator containing a completely demagnetized ferrite sample and solving

$$F(\epsilon_f', \mu_d', f_{r0}) = 0 \ , \qquad (1)$$

where f_{r0} is the measured H_{011} mode resonant frequency and F is the operator H_{011} eigenvalue equation. After determining μ_d', the imaginary part of the permeability

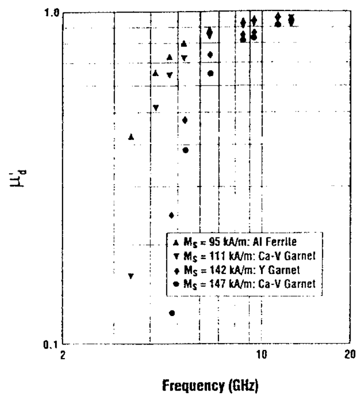

Figure 2: Measured relative permeability, μ_d', as function of frequency.

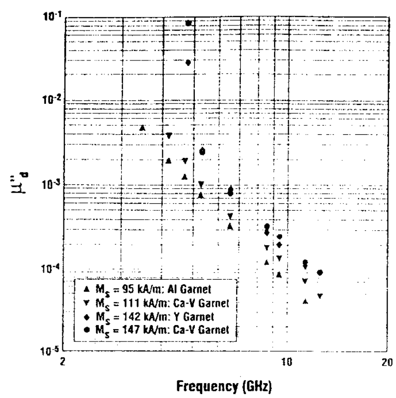

Figure 3: Measured relative magnetic loss factor, μ_d'', as function of frequency.

μ_d^* can be found as a solution to the equation

$$Q^{-1} = Q_c^{-1} + p_{\epsilon_r'} \tan\delta_{e,r} + p_{\epsilon_f'} \tan\delta_{e,f} + p_{\mu_d'} \tan\delta_{m,f} \ , \qquad (2)$$

where Q is the unloaded Q factor for the H_{011} mode, Q_c is the Q factor representing conductor losses in the metal plates, $p_{\epsilon_r'}$ is the electric energy filling factor for the dielectric ring resonator, $p_{\epsilon_f'}, p_{\mu_d'}$ are the ferrite sample electric and magnetic energy filling factors, $\tan\delta_{e,r}$ and $\tan\delta_{e,f}$ are the dielectric loss tangents of the ring resonator and ferrite, and $\tan\delta_{m,f}$ is the magnetic loss tangent of the ferrite. Example measurement data for several ferrites having differing saturation magnetizations M_s are shown in Figs. 2 and 3. Variational uncertainty analyses, which includes sources of error due to sample dimensions, surface resistance of the ground planes, resonance frequency and Q factor, were performed. The estimated total uncertainty in μ_d' is ± 0.8 percent and that in μ_d'' is $\pm 1 \times 10^{-5}$.

Schloemann [3] gives the following theoretical relation for the demagnetized relative permeability of a sample

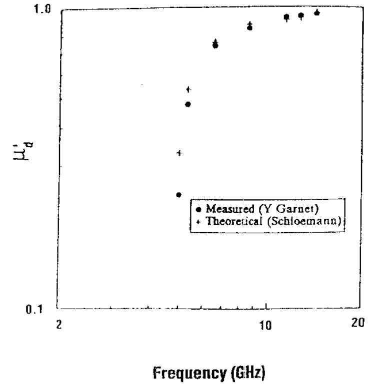

Figure 4: Comparison of demagnetized permeability measurements with theoretical predictions.

possessing a cylindrically symmetric domain configuration in terms of the saturation magnetization, the angular rf frequency ω, and the gyromagnetic ratio γ (35.19 MHz· m/kA),

$$\mu_d' = \frac{2}{3}\left[1 - \left(\frac{2\pi\gamma M_s}{\omega}\right)^2\right]^{1/2} + \frac{1}{3} \, . \qquad (3)$$

A comparison between measured μ_d' values and this predictive relation is shown in Fig. 4. For $2\pi\gamma M_s/\omega < 0.75$, the Schloemann theoretical prediction compares well with measurement data.

4 Summary

Microwave measurements of the scalar complex permeability of a *single* ferrite sample may be performed over a broad range in frequency using H_{011} dielectric resonators. Magnetic loss factors as low as 1×10^{-5} may be accurately determined. Theoretical predictions can provide useful estimates of demagnetized real permeability when $2\pi\gamma M_s/\omega < 0.75$, but nonlinearly varying magnetic loss factors must generally be measured at microwave frequencies.

5 References

1. R.A. Waldron, "Electromagnetic wave propagation in cylindrical waveguides containing gyromagnetic media," J. Brit. IRE, vol. 18, pp. 597-612, 677-690, 733-746, 1958.

2. A.J. Baden Fuller, *Ferrites at Microwave Frequencies.* London: Peter Peregrinus, ch. 3, 267 pp., 1987.

3. E. Schloemann, "Microwave behavior of partially magnetized ferrites," J. Appl. Phys., vol. 41, p. 204-214, 1970.